Chapter 21

Numerical Simulation on Seismic Behavior of UHTCC Beam-Column Joints

Wei Li

Additional information is available at the end of the chapter

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Abstract

To study the effects of ultra-high toughness cementitious composite (UHTCC) on the seismic behaviors of local enhancement beam-column joints under reversed cyclic loading, three specimens were tested and performed with half-scale interior joints in the finite element software Open System for Earthquake Engineering Simulation (OpenSees) and ANSYS in this chapter. The element "Concrete02" was used to simulate the material properties of UHTCC. The comparison of simulated results and experimental results indicated that displacement-beam-column element could be efficiently used to simulate the hysteresis response and the characteristic of energy dissipation of joints. The cementitious composites with ultra-high toughness could significantly improve the seismic performance of core area and had better ductility. Compared with ANSYS, the OpenSees finite element model was proved that preferably reflected the UHTCC enhanced nonlinear characteristic of frame nodes and effectively analyzed beam-column joint bearing capacity and seismic behavior.

Keywords: beam-column joint, OpenSees, ANSYS, numerical simulation, UHTCC

1. Introduction

Reinforced concrete (RC) beam-column joints were the vital components of structure that transfer and distribute internal forces and maintain structural integrity to ensure the safety. Most previous earthquake damage and research study showed that beam-column joints were vulnerable in seismic-prone areas and difficult to be repaired after the destruction. Accordingly, extensive research about the beam-column joints for seismic performance was triggered. From these research communities in the last decades, several studies focused on the application of steel fiber to enhance the joint shear strength or deformability, while the softening properties of concrete still existed. Ultra-high toughness cementitious composite

(UHTCC) [1–3], as one kind of reinforcing concretes was composed by polyvinyl alcohol fiber and cement paste as the interior performance was determined by micromechanics. Under the bending and tensile load, the UHTCC material exhibits pseudostrain hardening, high toughness, and great strain capacity under and multiple fine cracking behavior with the average crack width of 1 mm. Due to its superior strain behavior, UHTCC was an ideal material to replace the concrete in the joint zone of interior beam-column joints to substantially improve the load capacity and energy absorption capacity.

In this research, three half-scale interior beam-column joint specimens were tested. The results of the analysis and comparison of the numerical simulation data by ANSYS and Open System for Earthquake Engineering Simulation (OpenSees) can provide reference for the design and research of this kind of beam-column joints.

2. Experimental investigation

2.1. Experimental overview

To verify the toughness effectiveness of the UHTCC, three half-scale interior beam-column joint specimens whose core area was replaced by this material, as the specimen geometry was summarized in **Figure 1**, were tested. All the specimens had the same cross-sectional dimension (150 × 250 mm), and the detailed material parameters of concrete and UHTCC and summary of test parameters of beam-column joint specimens were listed in **Tables 1** and **2**, respectively. Axial compression ratio and volume-stirrup ratio were the main parameters. All material parameters of steel were uniformly presented in **Table 3**.

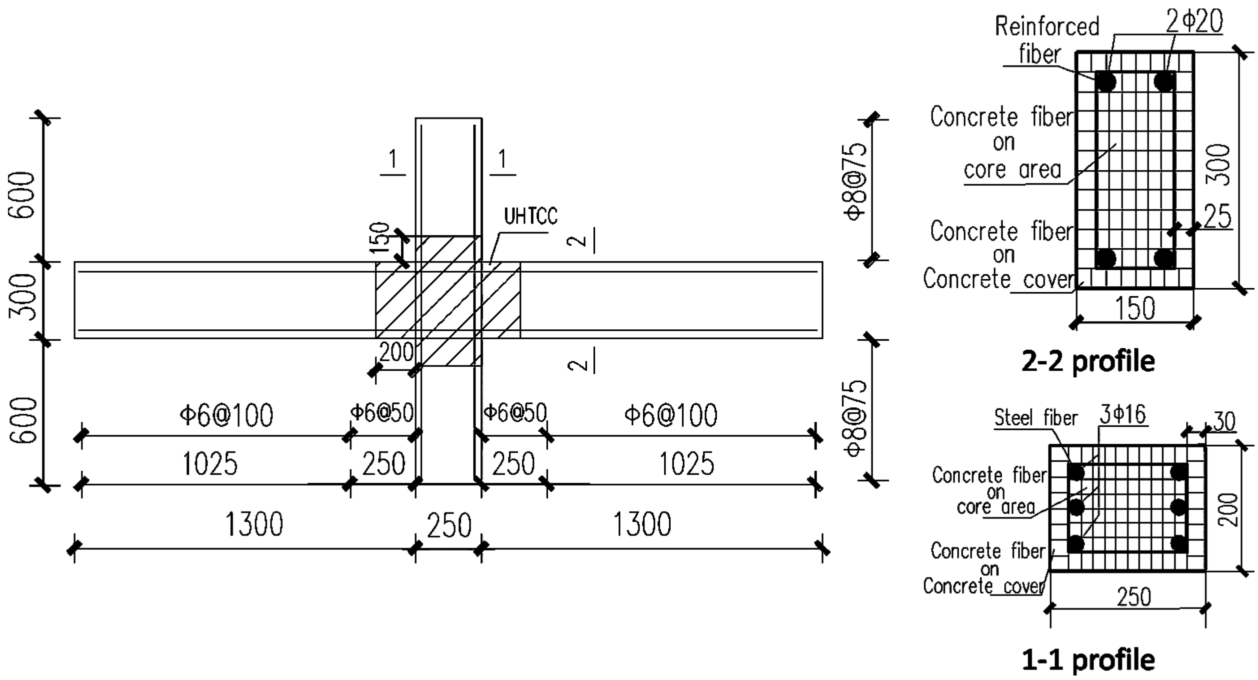

Figure 1. Specimen size and reinforcement figure.

Concrete cubic Compressive strength	Beam C30	Column C40	UHTCC
f_{cu}/MPa	31.95	45.78	40

Table 1. Material parameters of concrete and UHTCC.

Specimen	Volume-stirrup RatioV_f/%	Stirrup space	Axle pressure/kN	Axial compression Ratio n_1
Specimen 1	0.58	ϕ8@150	385	0.25
Specimen 2	1.17	ϕ8@100	540	0.35
Specimen 3	—	—	540	0.35

Table 2. Sample parameters.

Bar diameter	Yield strength f_y/MPa	Ultimate strength f_u/MPa
Φ6	319.55	490.56
Φ8	300.5	471.35
Φ16	386.55	572.92
Φ20	309.87	459.88

Table 3. Material parameters of steel.

2.2. Loading method

A schematic of loading modes was shown in **Figure 2**. All specimens were tested under a low-reversed cyclic load provided by a digital closed-loop controlled hydraulic loading system. The controlled value of axle pressure on the top of the column was adopted using a small hydraulic jack in load control, and low-reversed cyclic displacement controlled loading was applied on both free ends of the beam by means of a loading collar [4].

2.3. Test results

The final damage on the joint of UHTCC specimen was illustrated in **Figure 3**. The shear failure of the UHTCC beam-column joint occurs in the core area and this process includes four stages: initial crack, penetrating crack, ultimate state, and failure state. From the first stage to the end, the vertical crack first appeared in the inner end of the concrete beam. The cracks about 0.02 mm from the center of core area would appear with the continuous load. The fine inclined cracks would appear along the other diagonal direction when the reverse load was applied. With the increase of the magnitude of the load and the number of cycles, crack extended to the ends of the core area and significantly increased and finally formed a typical oblique X-type microcrack with 1 mm of the average crack spacing. According to the joints failure modes and fine cracks shown in **Figure 3**, the concrete surface in the core area did not spall, which was mainly due to the bridging stress provided by the PVA fiber in UHTCC enhanced the shear capacity of beam-column joints, so the specimen had multiple microcrack characteristic cracks under the ultimate load.

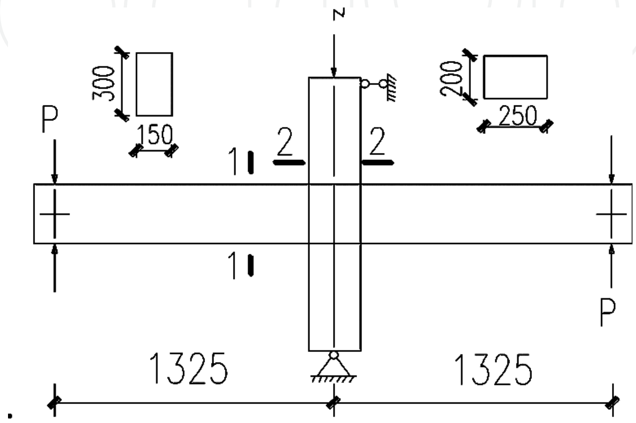

Figure 2. Loading method.

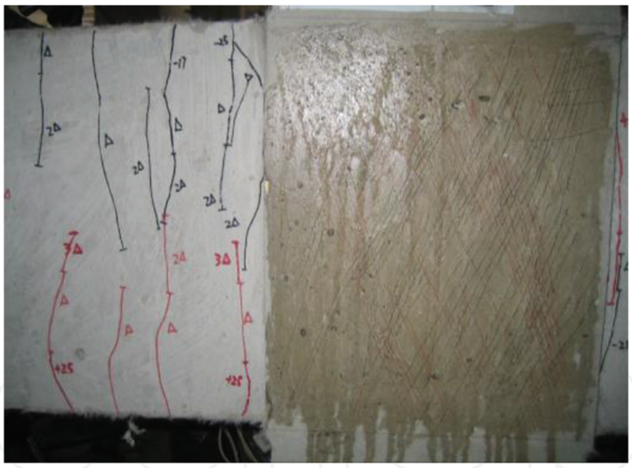

Figure 3. Damage on the joint.

3. Numerical study

3.1. The establishment of the model

ANSYS, a large-scale general finite element software across a range of disciplines, was used to simulate the response of beam-column joint. Depending on the size of the frame node

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specimens and the symmetry of the specimen, one-fourth solid was modeled appropriately to reduce the time consumption of computing. The Link8 element, the Solid65 element, and the combin39 element were, respectively, used to simulate the steel, concrete (include UHTCC), and bond slip in the specimen. According to the position of the steel, mapping method was chosen to divide the grid on the geometric entities with the unit size of 50 mm; meanwhile, the sideline was defined as steel.

In addition, in order to better satisfy the engineering demand and analyze overall responses of the new beam-column joint element, the Open System for Earthquake Engineering Simulation (OpenSees) software was also selected to stimulate all the specimens. OpenSees was the computational platform using modern software techniques to provide a common analytical research framework for both structural and geotechnical engineering research study [5, 6]. It had advanced capabilities for creating and analyzing effects in structural and geotechnical engineering using built-in models and solution algorithms.

In OpenSees, the unconfined and confined concrete in beam and column were all stimulated by the "Concrete02" material model that reflected compression behavior through two segments in the rise and fall polyline curve. In general, to ensure a smooth limit-state function the steel material was modeled by the "Steel02" material with a bilinear model. Nonlinear beam-column, force-based nonlinear beam-column element, was used to model each of the members with 2D fiber sections. For the same reason, as shown in **Figure 1**, the cross-sections of column and beam were all discretized into different fibers in the in-plane direction.

3.2. The numerical modeling results

The comparison of hysteretic curves and skeleton curve between numerical simulation and test was shown in **Figure 4**. The following conclusion might be drawn for the damage features of UHTCC through the observation and analysis of experimental and numerical simulation.

The area of hysteresis loop was narrow and small when the displacement was small. However, with the increasing number and time of cyclic loading, inclined cracks in the center of the core repeatedly opened and closed. Finally, degradation of specimen stiffness was serious and hysteresis loop was shown with inverse S-shaped in **Figure 4**. The pinching effect from software simulation results were not obvious; this may be because there were less parameters to define unit Pinching4 in the OpenSees and lead the inaccurate reflection of pinching effect with the test curve steeper than hysteresis curve in the unloading phase.

From the hysteretic curves and skeleton curve, all the numerical simulation captured the deterioration characters of the resistance after yielding and gave reasonable prediction on the initial stiffness, unloading stiffness, and reloading stiffness of the joint; however, compared with the ANSYS simulation results, the simulation of OpenSees was closer to the test.

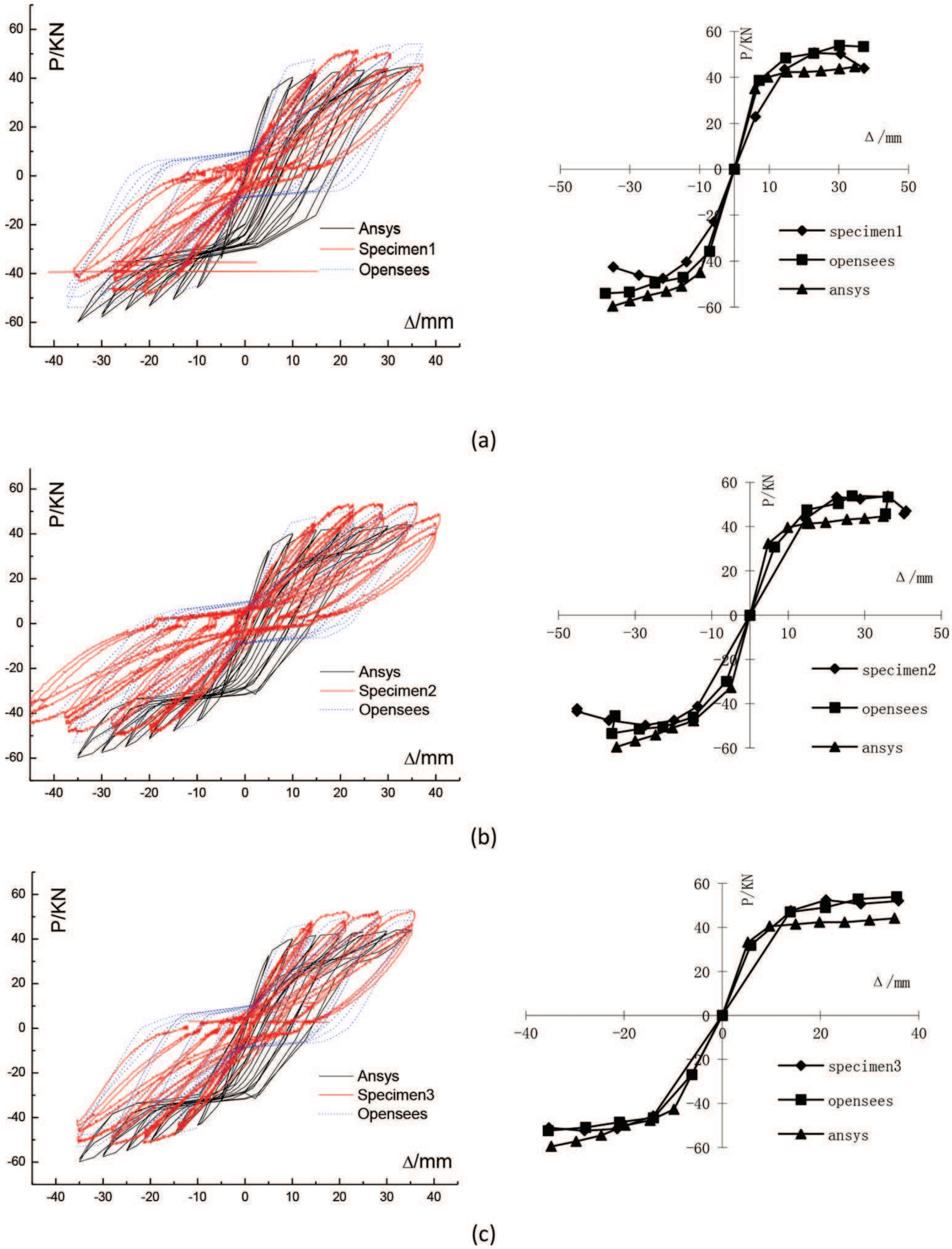

Figure 4. Comparison of hysteretic curves and skeleton curves: (a) Specimen1, (b) Specimen2, (c) Specimen3.

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4. Conclusions

The following conclusions could be drawn through the research of the mechanical properties of the UHTCC beam-column joints.

The shear failure occurs in all the core area of UHTCC beam joints. From the four failure stages begin to end, the UHTCC material showed ultra-high toughness and superior ability of dispersing cracks with a number of fine cracks (average 1 mm) appearing in the center of the joint core.

The specimens with the change of stirrups and axial compression ratio had no significant effect on the shearing resistance capability by the UHTCC used in the center of the core joint that had excellent shearing resistant property to replace or partially replace the amounts of stirrups.

ANSYS and OpenSees were all capable of capturing the connection of UHTCC beam-column joints from initial cracking to destruction, including column failure and shear panel failure mechanisms. But obviously OpenSees simulation results were better than ANSYS with lower cost on calculation and modeling.

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Author details

Wei Li
Address all correspondence to: weilee903@outlook.com

Center of Advanced Innovation Technologies, VŠB-Technical University of Ostrava, Ostrava-Poruba, Czech Republic

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